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PLASMA-SPRAYED METAL-GLASS AND METAL-GLASS FLUORIDE COATINGS FOR LUBRICATION TO 900° C

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PLASMA-SPRAYED METAL-GLASS AND METAL-GLASS FLUORIDE COATINGS FOR LUBRICATION TO 900° C

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ABSTRACT

Plasma-sprayed composites, which have good oxidation-resistance and self-lubricating characteristics to 900° C, were developed. The composites are a nichrome matrix containing dispersed glass for oxidation protection and calcium fluoride for lubrication; they are applied to bearing surfaces by plasma spraying layers about 0.050 centimeters thick which are then machined to 0.025 centimeters. Oscillating bearing tests were performed in air to 900° C at unit radial loads up to 3.5×10^7 N/M^2 (5000 psi) and a thrust load of 1960N (440 lbs). Bearings with a composite liner in the bore were in good condition after over 50,000 oscillating cycles accumulated during repeated, bearing temperatures cycles between 25° and 900° C.

INTRODUCTION

A need exists for the development of improved high-temperature, self-lubricating materials. In advanced aircraft, the aerodynamic heating at speeds of Mach 3 and higher can result in vehicle skin temperatures well above the temperature limitations of presently available airframe bearings. As an extreme case, a maximum skin temperature of about 1100° C has been predicted for the Space Shuttle Orbiter during reentry Fig. 1 (1). Airframe bearings and control surface seals for the Orbiter are near the heated surfaces. They must therefore either be capable of high temperature operation or suffer the weight penalty of cooling or insulation. Other areas in which high temperature lubrication is needed include sliding contact seals for automotive turbine regenerators, shaft seals for turbopumps, piston rings for high performance reciprocating compressors, and lubricants for hot glass processing machinery.

Solid lubricants such as graphite, molybdenum disulphide, and graphite fluoride oxidize or dissociate below 500° C (2 to 5). Self-lubricating composites of sintered porous Inconel, in which the pore structure is impregnated with calcium fluoride (CaF_2)-barium fluoride (BaF_2) eutectic, have been successfully tested for long duration in non-oxidizing atmospheres to 900° C (6). In air however, usefulness is limited to 650° C for long durations and 800° C for short durations because oxidation of the sintered metal structure occurs and causes swelling and distortion of the part. Attempts to reduce metal oxidation are described in reference 7. In that work, considerable improvement was achieved by partially filling the pore structure of the metal matrix with oxidation-protective glasses. The lubricating fluorides were introduced in a second infiltration. The resulting composites had improved oxidation resistance and were self-lubricating at 900° C. However, the double infiltration was complex and time-consuming. In the work described in this paper, the potentially simpler alternative method of preparing the composite by plasma-spraying was explored. Work by Blampin in France (8) had indicated that adherent CaF_2 and CaF_2-graphite coatings could be applied to metal surface by plasma spraying.

This paper describes the tribological and oxidative behavior of plasma-sprayed composites of CaF_2, glass and metal that were developed in our program. The scope of the experiments included: (1) basic friction and wear measurements using a pin on disk apparatus; (2) oxidation studies by thermo gravimetric analyses (T. G. A.) and dimensional changes; (3) and finally actual bearing tests of self-alining, plain cylindrical bearings in which either the bore or the oscillating journal were coated with the plasma-sprayed composite. Bearing tests were at unit radial loads up to 3.5×10^7 N/M^2 (5,000 psi), a thrust load of 1960 N (440 lb), and temperatures to 900° C. Journal oscillation was ±15° at a frequency of 1 hertz.

PREPARATION OF COMPOSITE MATERIALS

The composites were deposited by plasma spraying mixed powders of nichrome, glass and in some cases CaF_2. The coatings were applied to metal disks, bearing journals and bearing bores. All substrates were made of the precipitation-hardening nickel-chromium alloy René 41.

PREPARATION OF POWDERS FOR PLASMA/SPRAYING

Glasses have been used as oxidation protective coatings for metals, (9, 10). The glass used in our composites was based on one of the formulation originally developed under a NASA contract (9) to explore protective coatings for gas turbine blades. The composition of the mill batch or starting material from which the glass used in our work was made, and the calculated final compositions of the glass are given in table I. The difference in mill batch and glass compositions are caused by the loss of carbon dioxide from the carbonates and water from the hydrated materials used during preparation of the glass.

The mill batch was melted in a nickel crucible at 1370° C. About 10 minutes were allowed for complete decomposition of the carbonates and hydrated compounds. The melt was then poured into water to form readily pulverized, shot-like particles of glass frit. The frit was pebble-milled dry to a powder which would pass through a U. S. Standard sieve No. 120. (Particles sizes less than 125 micrometers.)

The powdered glass was then mixed with powdered nichrome metal and, in one formulation, with CaF_2 to the desired compositions for plasma spraying. Two compositions of sprayed powder used were:

(1) 80 w/o nichrome - 20 w/o glass

(2) 67 w/o nichrome - 16.5 w/o glass - 16.5 w/o CaF_2.

Plasma spraying procedure

The substrate surfaces were grit blasted with coarse alumina grit. The composites were sprayed to a thickness of about 0.050 centimeters and subsequently machined back to a thickness of 0.025 centimeters.

During spraying argon was used as the carrier gas and the arc gas. An arc current of 350 amperes was used.

Machining the Plasma Sprayed Coatings

The recommended machining procedure is very simple, but must be done correctly to prevent excessive smearing of the nichrome metal over the machined surface. It is very important that the surface areas occupied by the nonmetallic components of the composite are not diminished by metal smearing during machining. The following procedure has produced the best surfaces to date with the least amount of smeared and folded metal.

1. Machine dry
2. Use a single-point carbide tool
3. Machine at low speed of 9 to 12 M/min (30-40 ft/min)
4. Remove no more than 0.010 centimeter (0.004 in.) per cut

Post-machining surface treatments. - Any machining smears that do occur can be removed and surface finish can be improved by wet sanding with sand paper progressing from 150 grit through at least two intermediate grades to 600 grit.

For those composites containing CaF_2, the surface can be enriched in the lubricant by heat treating the specimens in air at 870° C for four hours. The heat treatment causes a solid state migration of fluorides along the surface and serves the added beneficial purpose of mildly pre-oxidizing the exposed metal. The surface become entirely covered with a combined fluoride-oxide film which is very desirable to prevent direct metal to metal adhesive contacts during sliding. For those composites without CaF_2, the pre-oxidation alone is beneficial. Photomicrographs of a nichrome-CaF_2-glass composite surface before and after heat treatment are given in (fig. 2).

Friction Apparatus

The friction apparatus used in this work has been previously described, eq, (5) The sliding specimens consist of a pin with a 0.476cm hemispherical radius at one end in sliding contact under a load of 1-kg with the flat surface of a rotating disk. The disk is coated with the experimental self-lubricating material. The pin generates a 6.3cm diam. circular wear track on the coated surface (sliding speed of 160cm/sec).

Test Bearings

The design of the test bearing is illustrated in (fig. 3). The general design is that of a rod end spherical bearing. However, in this program, the spherical element was not fastened to the journal but was allowed to float. The self-lubricating composite layer was plasma sprayed on the journal or on the bearing bore and one thrust surface. The coatings were machined to a thickness of 0.025 centimeter (0.010 in.), sanded to remove machining marks then heat-treated as previously described. All bearing elements and the journal were subjected to the heat treatment so that all exposed surfaces were mildly oxidized prior to operating the bearings. The journal oscillated in the bore.

All bearing elements (except the self-lubricating layer in the bore) were made of René 41, a precipitation hardenting nickel alloy. The bearings were hardened to Rockwell C-32 (which is not reduced by the composite heat treatment). The lined bearing bore was 1.537 centimeters (0.605 in.) diameter and 1.9 centimeters (0.75 in.) long. The spherical diameter was 2.92 centimeters (1.151 in.). The clearance between the journal and the composite-lined bore was 0.013 centimeters (0.005 in.), and the ball/outer race clearance was 0.008 centimeter (0.003 in.).

BEARING TEST MACHINE

A detailed description of the bearing test ring is given in (1); a drawing is given in (fig. 4). In essence, the test bearing is mounted in an induction-heated bearing housing. The oscillating journal is taper-mounted into a drive shaft which is supported at both ends by roller bearings. Radial and thrust loads are applied to the test bearing by hydraulic actuators suitably linked to the drive shaft. The drive shaft is oscillated by means of a reversible hydraulic actuator which simulates the motion in an aircraft control surface actuator and bearing assembly. Thermocouples are press-mounted against the bearing outer race and in some cases embedded in the bearing ball (see fig. 3).

BEARING TEST PROCEDURE

The simulated reentry tests consisted of beginning bearing oscillation at room temperature under a nominal unit radial load of 4.5×10^5 N/M^2 (65 psi) then increasing the unit load in 7×10^6 N/M^2 (1000 psi) increments (2 minutes at each increment) up to the test load of 3.5 3.5×10^7 N/M^2 (5000 psi). Unit radial load is defined as the total radial load per unit projected area of the bearing bore where projected area is obtained by multiplying bore diameter by bore length. A thrust load of 1960 N (440 lb) was also applied. The bearing temperature was controlled during the tests to obtain the temperature time profile shown in Fig. 5. No attempt was made to simulate other reentry profiles such as load or atmospheric pressure. All tests were conducted in room air.

RESULTS

Oxidation Studies

The oxidation rate of the metallic structure in sintered or plasma sprayed composites is an important factor in their high temperature performance. Oxidation weakens the composite by the formation of relatively weak oxides at the expense of the supporting metallic structure. Perhaps, even more significantly, oxidation can cause swelling and other undesirable distortions. When the composites are used in bearings, these distortions ultimately cause a loss in working clearance and the bearing can jam. For self-lubricating composites, which are to be used to high temperatures in air, it is therefore important to control oxidation in order to maintain both the strength and the dimensional stability of the material.

The oxidation data, which was obtained by TGA for a number of nichrome-glass and nichrome-glass-CaF_2 composites, are given in Fig. 6. The highest oxidation rates were observed with porous sintered nichrome which had been completely infiltrated (about 10 w/o) with glass, then coated with a thin film of CaF_2/BaF_2 eutectic. When the fluoride eutectic overlay was omitted oxidation was one third lower. This composite was previously shown to have excellent oxidation resistance, at 816° C, (7) but as indicated in Fig. 6, after 240 hours at 900° C, metal oxidation was almost 30 percent theoretically complete for the composite with the fluoride coating and almost 20 percent complete for the uncoated composite. Later plasma sprayed composites containing 20 w/o glass had better oxidation properties. For example, the data show that plasma sprayed nichrome with 20 w/o of glass oxidized only, about 15 w/o after 240 hours at 900° C. When a fluoride overlay coating was bonded to the surface of the plasma sprayed coating, no signifcant difference in oxidation rate was observed. The apparent beneficial effect was probably within the experiment error. The lowest oxidation rate was obtained with the plasma sprayed coating containing nichrome, CaF_2, and glass. Only about 7 percent of theoretically complete oxidation occurred after 240 hours at 900° C.

It is not clear why CaF_2 increases the oxidation rates of nickel chromium alloy used in composites prepared by sintering and infiltration yet actually appears to reduce metal oxidation in the plasma-sprayed composites. Increased oxidation in the first case can be explained by the occurrence of oxide solid state diffusion away from the parent metal surface and into the fluoride filler. This oxide dilution on the metal surface reduces the efficiency of the oxides to form protective films on the metal surfaces in the usual manner. Reduced oxidation rates when CaF_2 is introduced into the plasma-sprayed coatings appears to be contradictory. However, it was observed that plasma sprayed nichrome-glass-CaF_2 coatings were denser (less porority) and more homogeneous than coatings containing only nichrome and glass. It can only be speculated at this time that these improvements in coating quality imparted by

CaF_2 had a beneficial effect on oxidation characteristics that outweighed any undesirable effects attributable to dilution of oxide films.

Table II gives the increase in thickness of composite coatings (initially 0.025 cm thick) during the first 4 hours and the next 236 hours of the 900° C oxidation tests. The increase in thickness in the first 4 hours was partially caused by extrusion of CaF_2 from the surface pores. The extruded material forms microscopic mounds on the surface. The height of the mounds is included in the micrometer measurements of coating thickness. The extruded material not only forms mounds but gradually migrates away from the mounds until the surface is entirely covered with a thin film of CaF_2 and metal oxide (fig. 2). Some increase in surface roughness occurs because the film is thicker at the mounds than elsewhere. (A smooth finish can be readily restored by lightly wet sanding with waterproof sandpaper. With care it is possible to restore a good finish without removing the beneficial film.) The increase in thickness during the remaining 236 hours was typically 1×10^{-3} cm and was possibly caused by metal oxidation. This increase represents only 4 percent of the initial 0.025 cm coating thickness.

Friction and Wear Tests Using a Pin on Disk Apparatus

Typical friction coefficients for three plasma sprayed composites are shown in (fig. 7). The data show the importance of proper surface-conditioning and the effect of CaF_2 addition to the nichrome-glass composite. Considerably higher friciton coefficients were observed with specimens in the as machined condition compared to those which were sanded and heat- treated after machining.

Of the two composites which were sanded and heat-treated the one containing CaF_2 gave the lower friction coefficients over the entire temperature range. It is interesting however that proper surface conditioning was even more effective than CaF_2 additions indicating that the glass also performs a lubricating function in these composites. The nichrome-CaF_2-glass coatings had a friction coefficient of around 0.4 at room temperature and this steadily decreased to about 0.2 at 900° C. Photomicrographs of the sliding surfaces after test are given in (fig. 8). The wear track on the disk is covered with a transparent, very smooth glaze; the wear scar on the René 41 pin is also covered with a similar glaze.

The wear coefficients for the nichrome-CaF_2-glass coatings and for the René 41 pins at room temperature, 540° C, and 900° C are given in (fig. 9). These data are compared to data from (12) for the wear of brass sliding on hardened tool steel and the wear of hardened tool steel on itself at room temperature. Comparability is reasonable here because both our data and the reference data were obtained on bench wear test machines which employed a concentrated, counterform type of contact. (Pin on disk in our work, crossed cylinders in Archard's work). However, in the bearing tests to follow, which involved conforming cylindrical contact, wear coefficients of the composites were consistently much lower than those obtained on the wear testers.

Bearing Tests - Wear

The bearing temperature-time profile used in the bearing tests is given in (fig. 5). Table III gives the average wear of the plasma sprayed composites over the entire temperature profile and at a bearing unit radial load of 3.5×10^7 N/M^2 (5000 psi) and a thrust load of 1960 N (440 lb). In some tests the journal was coated, in others the bearing bore was coated. The wear data given are total radial wear (cm increase in radial clearance due to wear) and calculated volume wear coefficients.

In bearings 1-5, table III, the lubricant was nichrome-glass bonded to the journals. One of the first observations with bearing 1 was the establishment of well-glazed rubbing surfaces early in the bearing test (run-in). This was very beneficial in reducing subsequent wear. This was true only if the coating did not spall and if the initial wear debris were removed from the bearing. After the first 10^4 oscillations, the radial wear of bearing 1 was 5×10^{-3} cm. However, the wear debris was then cleaned from the bearing and no additional measurable wear occurred during subsequent test, of up to a total of 3.8×10^4 oscillations. Some coatings on the journals had a tendency to spall at the bond line in the region of high load. This was usually followed by a rapid increase in bearing wear and torque. In bearing 5 for example, wear could not be accurately measured because of the severe surface damage caused by the spalled material. It was observed that spalling did not occur in coating applied to the bearing bore instead of the journal, for example bearings 6-9.

The differences in the spalling behavior of coatings on the journal and on the bore are probably due to the difference in mechanical stress distribution within the composite during bearing operation. When the coating is applied to the journal, the dense metal substrate reinforces the composite only against normal compressive stresses. Tangential stresses generated by sliding friction must be absorbed entirely by the coating and the coating bond to the substrate. On the other hand, when the coating is in the bearing bore, the bearing substrate material provides considerable lateral support to the coating and reinforces the composite against tangential as well as compressive stresses. When the difference in spalling behavior became clear, all susequent bearings were coated in the bearing bore.

Favorable results were obtained with the nichrome-CaF_2-glass composite as a self-lubricating liner in the bearing bore. In general wear rates with this material were lower than they were with the nichrome-glass composites. In fact, during the first 12×10^3 oscillating cycles (3 reentry tests) with bearings 7 and 9, no wear was detectable by micrometer measurements on either the bearing bore or the journal. However, when the bearing was subjected to repeated tests without cleaning the bearing between tests, wear debris eventually accumulated within the bearing. These wear particles then had an abrasive effect and caused and accelerating wear process. This is indicated by the increase in the average wear coefficient with total accumulated shaft oscillations. Wear is therefore a self-accelerating process in this type of bearing unless some means are employed to continuously remove wear particles as they form. In fact, if wear debris is removed as previously indicated for bearing 1, the wear rate actually decreases with test duration.

The 0.025 centimeter thick liner of nichrome-CaF_2-glass in bearing 9 was almost worn through after twelve simulated reentries with no provision for wear debris removal. This quantity of wear is representative only for the test condition used. Most of the wear took place during the long period of operation below 500° C during the cool down portion of the tests. Pin on disk wear data and the bearing-wear data in table IV indicate that wear below 500° C is much more severe than it is above 500° C. Therefore whether the bearing would survive ten or a hundred reetries is strongly a function of the number of oscillations below 500° C in each reentry as well as whether or not provision is made for continuous wear debris removal.

Bearing Tests - Friction

Bearing friction from room temperature to 900° C is given in (fig. 10). Data are given for a preoxidized but otherwise unlubricated bearing, and for a bearing with a nichrome-CaF_2-glass liner in the bore. At a radial load of 3.5×10^{7} N/M^{2} (5000 psi), the unlubricated bearing exhibited higher friction throughout and seized at about 870° C. For the lubricated bearing friction coefficients were about 0.35 at room temperature and steadily decreased to about 0.20 in the temperature range of 500° to 900° C. The friction coefficient was sensitive to bearing load as shown in (fig. 11), friction at room temperature tended to decrease linearly with increasing load between 3.5×10^{6} and 3.5×10^{7} N/M^{2} (0.5 to 5×10^{3} psi). At 760° C and 900° C bearing temperatures, friction increased sharply as loads were reduced below 1×10^{7} N/M^{2} but at room temperature the load effect is linear over the entire load spectrum.

The friction coefficients given in (fig. 10 and 11) are typical, but scatter occurred in the friction coefficients. (Fig. 12)gives the scatter bands for friction coefficients observed during 12 reentry tests on the same bearing. (Bearing 9 of table III). The friction-time and friction-temperature profiles are superimposed and there is a common time scale on the abscissa. The general characteristic of lower friction at the higher temperature is apparent. (Fig. 12 (a)) gives the data during the first 3 tests and (fig. 12 (b)) gives data for the remaining 9 tests. Data scatter is less and the average friction level tends to be lower in the last 9 tests.

CONCLUSIONS

1. A promising coating material formulated in this program is a plasma sprayed composite of nichrome-16.5 w/o CaF_2-16.5 w/o glass. In addition to good high temperature friction and wear properties, this coating has good oxidation resistance to 900° C, it is machinable, and has excellent bond strength on the substrate metal.

2. In general, better results were obtanined with the coating on the bearing bore rather than on the journal surface.

3. Bearings were successfully operated during as many as twelve repeated temperature cycling tests. Friction coefficients were about 0.35 at room temperature and steadily decreased to about 0.20 in the temperature range of 500 to 900° C. Wear rates were very low during the first few tests (about 10 kc journal oscillations), but tended to increase as wear debris accumulated in the bearing clearance. Most wear debris was generated below 500° C during the cooling portion of

the bearing tests. Therefore any reduction in required oscillating cycles below 500° C or provision for continuous wear debris removal would increase bearing life.

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TABLE I. - COMPOSITION OF OXIDATION-PROTECTIVE GLASSES

W/O			
Initial mill batch composition		Final glass composition	
SiO_2	53.4	SiO_2	58.0
BaO	19.6	BaO	21.2
$Ca(OH)_2$	9.5	CaO	7.8
K_2CO_3	17.5	K_2O	13.0

TABLE II. - SWELL OF NICHROME COMPOSITES AFTER HEATING IN 900° C AIR

Composite composition	Increase in thickness of composites initially 0.025 centimeter thick		Comments
	During first 4 hours	During next 236 hours	
w/o	cm	cm	
67 NiCr, 16.5 CaF_2 16.5 Glass	2.5×10^{-3}	1.0×10^{-3}	Initial increase is partly extrusion of fluoride from surface pores
80 NiCr, 20 Glass	1.3	1.3	
80 NiCr, 20 Glass Fluoride overlay	1.5	1.3	
90 NiCr, 10 Glass	0.5	1.0	Sintered Inconel, glass infiltrated
90 NiCr, 10 Glass Fluoride overlay	1.5	2.0	" "

TABLE III. - WEAR AND AVERAGE WEAR COEFFICIENTS OF 0.025 cm THICK COMPOSITE COATINGS IN VARIABLE TEMPERATURE BEARING TESTS

[25°-900° C, 3.5×10^{7} N/M^{2} (5000 psi) unit radial load, 1960 N(440 lb) thrust load.]

Coating modification	Bearing number	Total shaft oscillations, 10^{3} cycles	Total radial wear, 10^{-3} cm (10^{-3} in.)	Average wear coefficient for test 10^{-11} cm^{3}/cm-kg	Comments
Nichrome-20 w/o glass on journal	1	10.5	5 (2)	100	Bearing 1 was cleaned between each of 3 tests. Additional wear after 10.5 kg not detectable this result shows beneficial effect of run-in if initial wear debris is removed
		23.2	5 (2)	46	
		38.0	5 (2)	29	
	2	11.7	4 (1.5)	70	
	3	23.0	17.5 (6.9)	210	Small amount of spalling
	4	24.0	48 (19)	630	Coatings spalled to cause high wear well into substrate metal
	5	6.0	Severe surface damage		
Nichrome-20 w/o glass in bearing bore	6	3	5.4 (2.1)	384	
Nichrome-16.5 w/o CaF_2 16.5 w/o glass in bore	7	12	< 0.25 (0.1)	< 2	Average wear coefficient increases with test duration due to abrasive action of entrapped wear debris (bearings ran full cycles shown without stops to remove wear debris).
	8	20	2.6 (1)	22	
	9	12	< 0.25 (0.1)	< 2	
		54	23 (9.0)	126	

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TABLE IV. - INFLUENCE OF TEMPERATURE ON WEAR OF~025 cm THICK COMPOSITES IN BEARING TESTS

[3.5×10^{7} N/M^2 (5000 psi) unit radial load, 1960 N(440 lb) thrust load, $\pm 15^{o}$ shaft oscillation at 1/3 or 1 Hz. Temperatures as specified in table.]

Coating modification	Bearing number	Temperature, ^{o}C	Total shaft oscillation, 10^3 cycles	Total radial wear, 10^{-3} cm (10^{-3} in.)	Average wear coefficient, 10^{-11} $cm^3/cm\text{-}kg$	Comments
Nichrome-20 w/o glass on journal	10	25-500	7.1	10 (4)	360	
	11	25-500	7.3	7.6 (3)	250	
	1	25-900	10.5	5 (2)	100	Ref. Table III
	12	650	7.9	2.6 (1)	57	

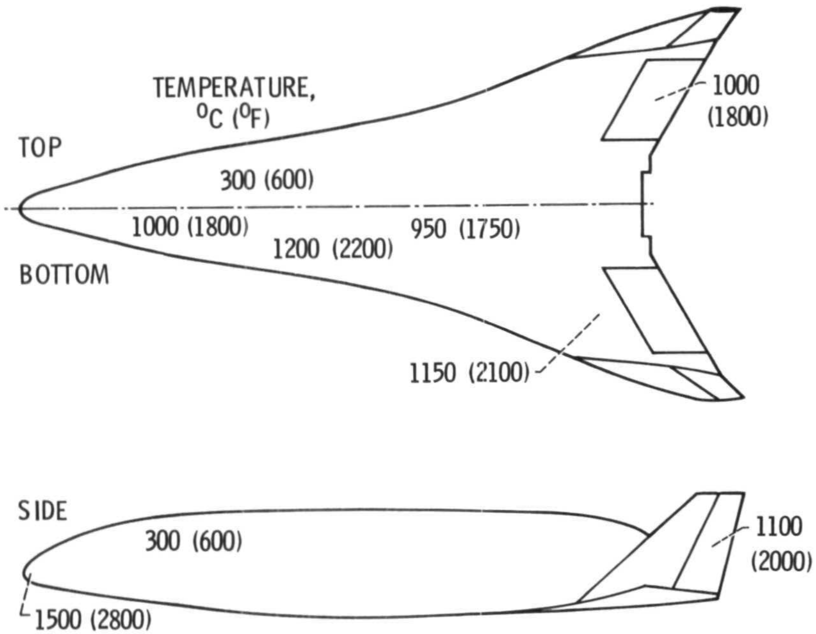

Figure 1. - Approximate temperature distribution for one concept of space shuttle orbiter (ref. 1).

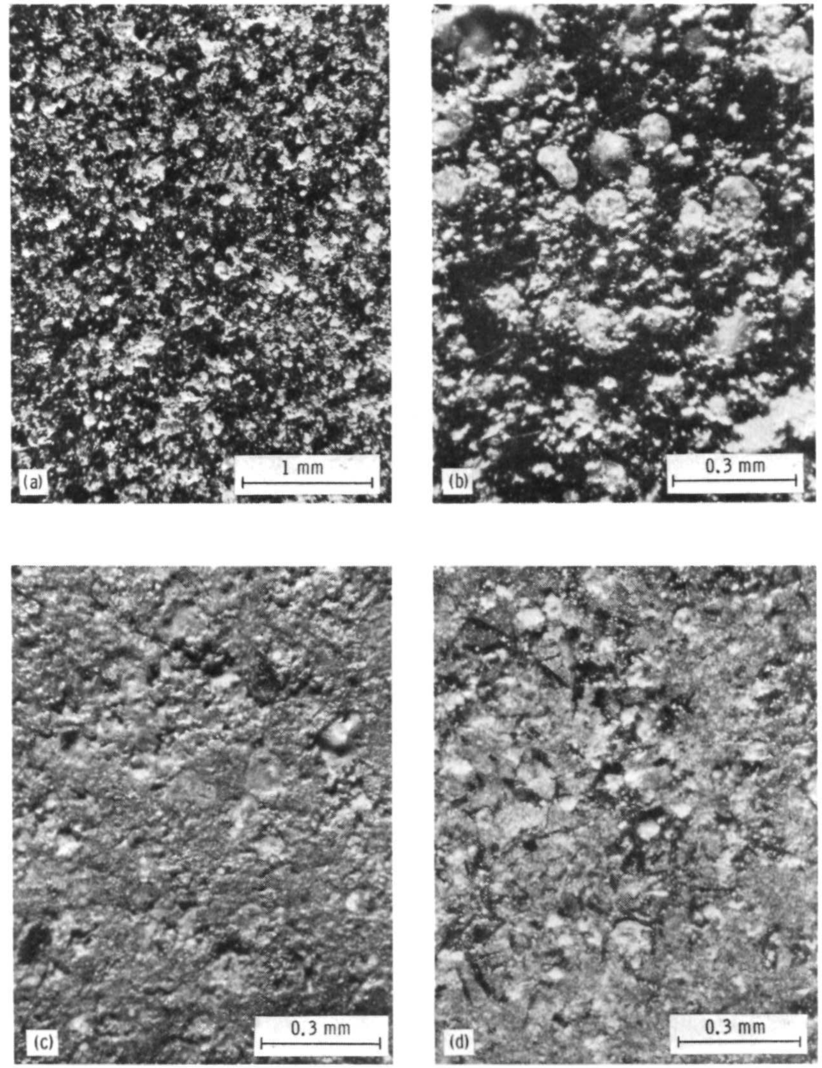

Figure 2. - Photomicrographs of plasma-sprayed nichrome-CaF_2-glass after different surface-conditioning pretreatments. (a) and (b) Machined and sanded; (c) same plus heat-treated in air 4-hours at 816° C; (d) heat-treated in air 20-hours at 816° C.

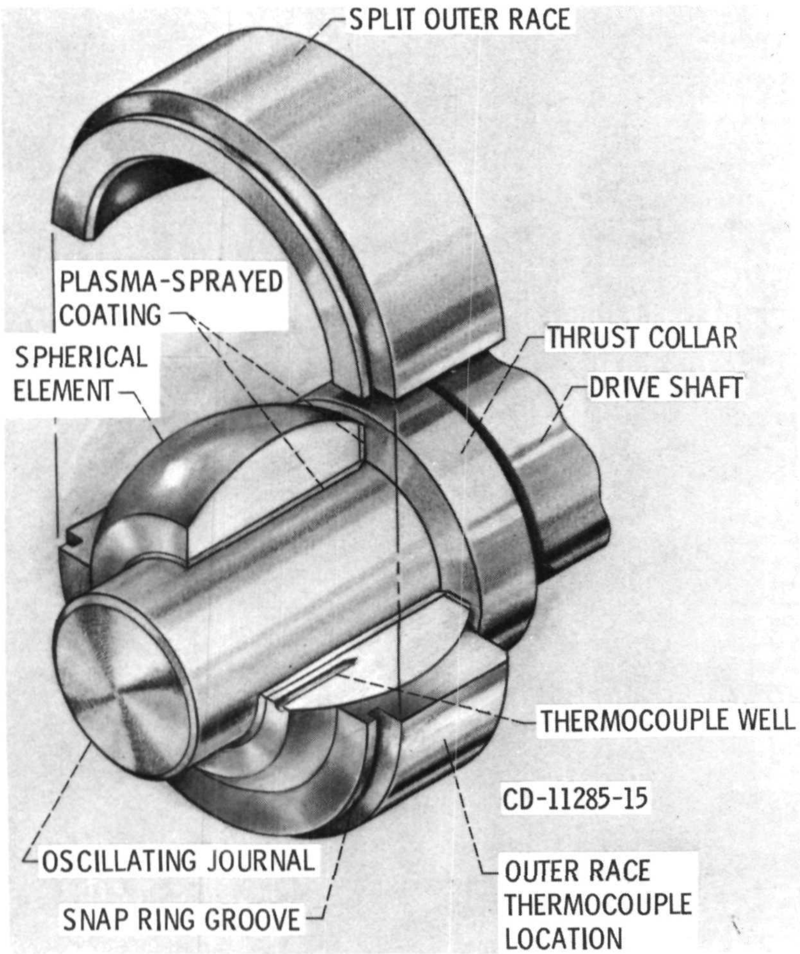

Figure 3. - Spherical test bearing.

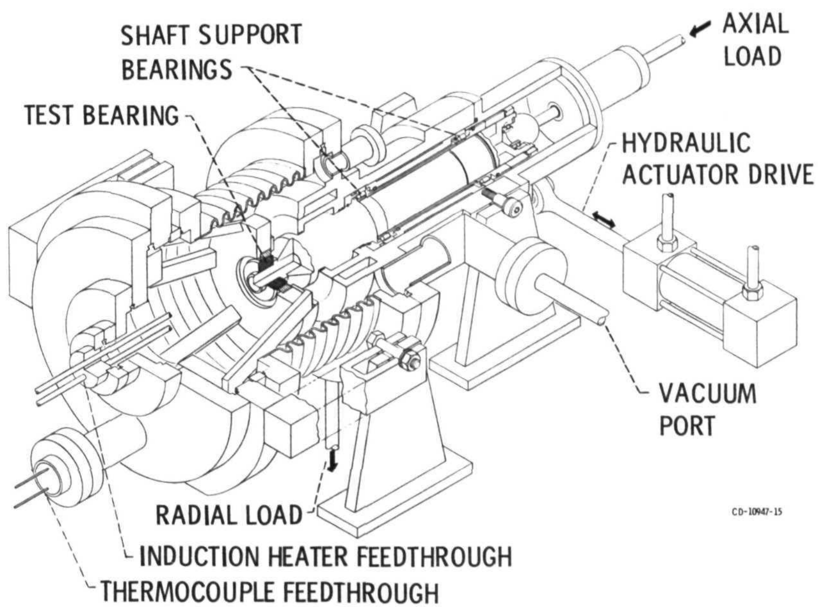

Figure 4. - High-temperature oscillating bearing test rig.

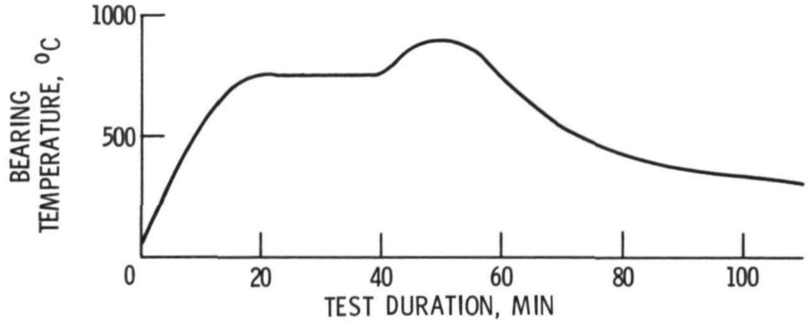

Figure 5. - Bearing test temperature profile. This is an estimated reentry temperature profile for shuttle airframe bearings without thermal protection.

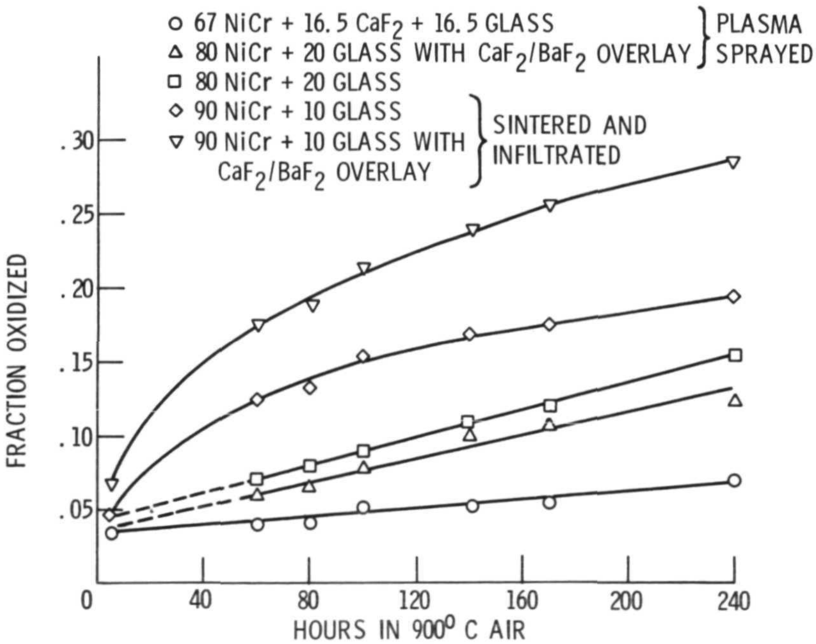

Figure 6. - Oxidation of nichrome matrix in various self-lubricating composites.

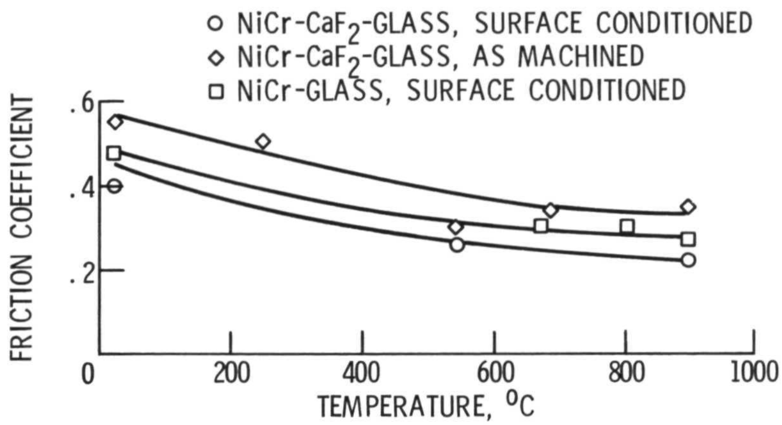

Figure 7. - Friction of some plasma-sprayed composites in pin on disk experiments. Load, 1 kg; 160 cm/sec; 600 rpm.

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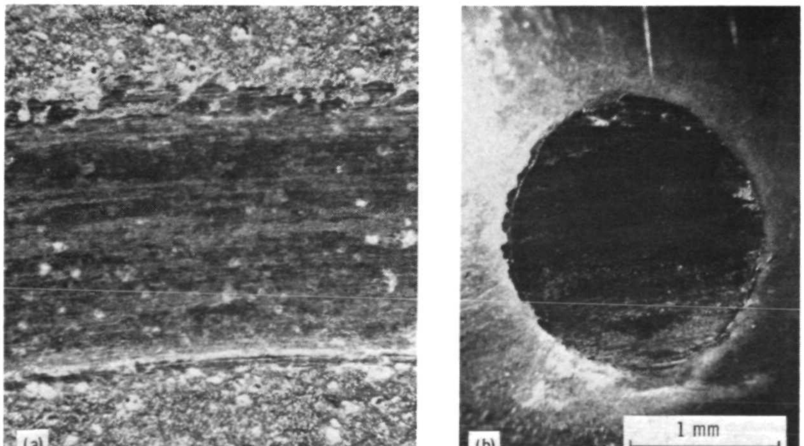

Figure 8. - Photomicrographs of sliding surfaces on (a) plasma-sprayed coating and on (b) René 41 pin. Load, 1 kg at 160 cm/sec (600 rpm); room temperature to 900° C test temperatures. Coating composition, nichrome-16.5 w/o CaF_2-16.5 w/o glass (heat-treated 4 hours at 816° C before friction and wear test).

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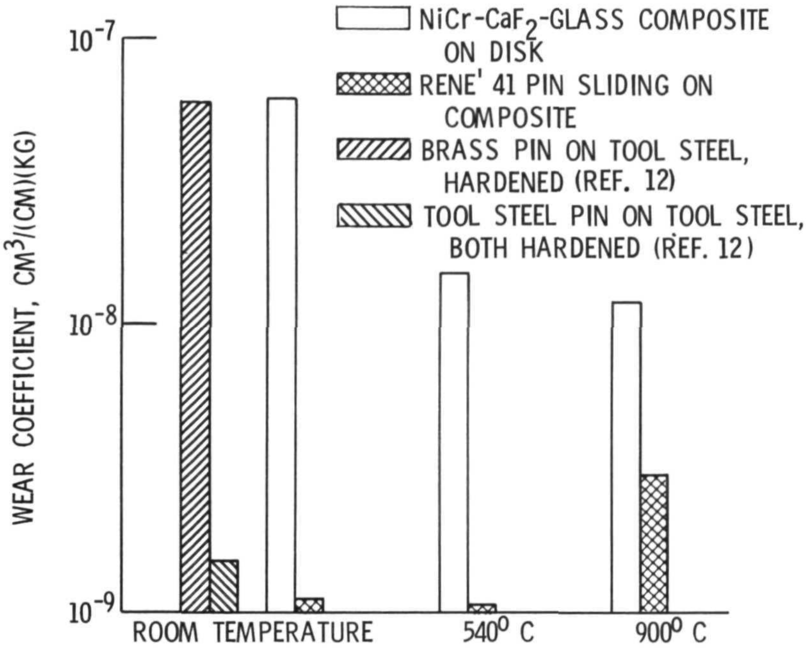

Figure 9. - Wear during pin on disk experiments. Load, 1 kg; 160 cm/sec; 600 rpm.

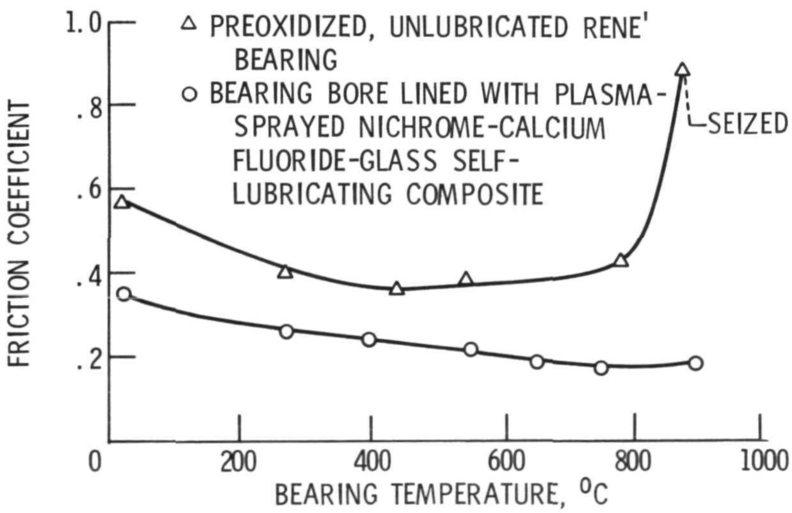

Figure 10. - Friction of self-aligning plain cylindrical bearings. Unit radial load, 3.5×10^7 N/M^2 (5 ksi); thrust load, 1960 N (440 lb); $\pm 15^0$ oscillating journal at 30 cpm.

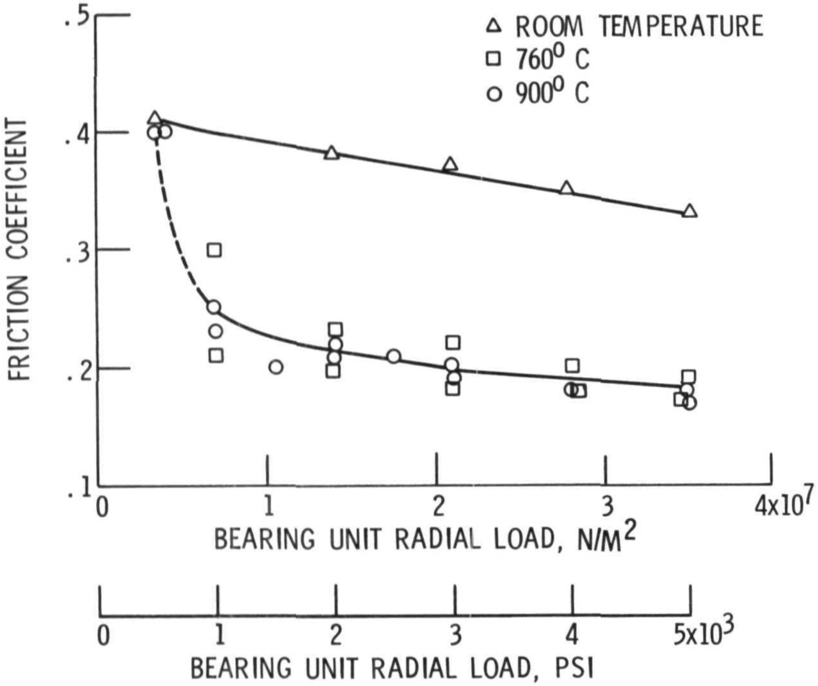

Figure 11. - Effect of load on friction of bearings with NiCr-CaF_2-glass composite liner in bore.

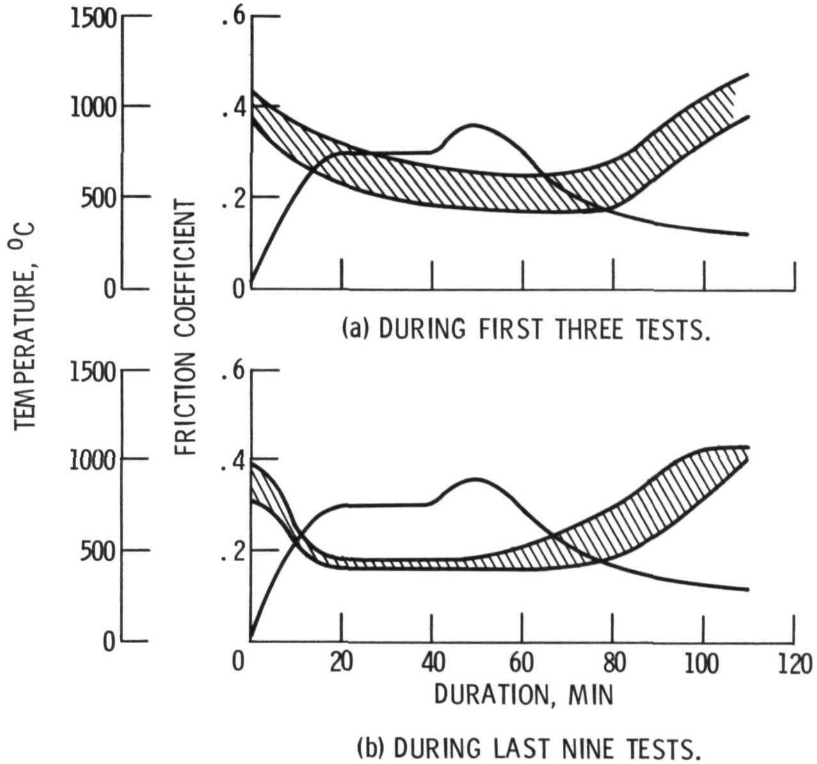

Figure 12. - Bearing friction scatter during twelve simulated reentry temperature tests with the same bearing composition of liner in bearing bore: Nichrome-$16\frac{1}{2}$ w/o CaF_2-$16\frac{1}{2}$ w/o glass.

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